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# Cavitation in MicroElectroMechanical Systems (MEMS): Importance, Deviations from Conventional Scale, and Preliminary Results

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## ABSTRACT

Hydrodynamic cavitation in micro systems is a fundamental engineering problem that is poorly understood. The lack of knowledge on cavitation relevant to MEMS devices is impeding the practical realization of novel high-velocity microfluidic machines. This paper divulges differences between cavitation occurring inside micro and conventional systems, and also indicates the limited applicability of conventional knowledge to predict and understand cavitating flows in micro-domains. A detailed discussion delineating the possible reasons of such a divergence is presented in this article. Additionally, selected results obtained from preliminary experiments on cavitation in micro-domains are presented.

## 1. INTRODUCTION

Recent advances in MicroElectroMechanical Systems (MEMS) technology has enabled the development of numerous high liquid velocities micro fluidic devices such as micro-rockets [1-4], micro-coolers [5,6], micro-refrigerators [7], micro and nano satellites [8-10], micro power systems including launch vehicles and high density power sources, electronic chip cooling systems, chemical micro-reactors [11,12], and DNA synthesis and bio-MEMS systems [13,14]. These devices have length scales between 1-1000 microns, $10^3$-$10^4$ times less than conventional machines, and operate at liquid speeds up to 200-300 m/s. It has been confirmed that microfluidic systems like their large-scale counterparts are susceptible to the pernicious effects of cavitation when apposite hydrodynamic conditions develop [15-19]. Literature review of cavitation in micro systems reveals that until February 2005 only a solitary journal paper [15], one conference paper [18], and one master thesis [19] have been devoted to this subject. Clearly the importance and complexity of the cavitation phenomenon necessitates considerable attention from the cavitation as well as the MEMS communities. This is especially important since some of these studies have yielded unexpected results and major deviations from conventional scale behavior.

The pernicious effect of hydrodynamic cavitation on conventional fluid machinery has been recognized and actively researched in the last century [20-28]. Cavitation in hydraulic machinery can limit performance, lower efficiency, introduce severe structural vibration, generate acoustic noise, choke flow and cause catastrophic damage [29-33]. Classical theory for scaling cavitation states that the cavitation number is sufficient to link one cavitation flow state to another provided the form of the flow field and its boundaries remain geometrically and kinematically similar. However, it has long been recognized that real flows often do not obey the classical theory because of so called “scale effects”, which arise from changes in velocity, size, fluid properties, and cavitation nuclei. In many cases it is impractical to accurately scale cavitation. Microfabricated Power-MEMS geometries differ considerably from their conventional-sized counterparts. Additionally, they operate under different Reynolds numbers (viscous effect), surface roughness and irregularities (surface nuclei and viscous effect), component materials (surface nuclei), nuclei size and distribution, and resident time (stream nuclei). When considering the reasons stated above along with the long lasting belief that nuclei together with viscous effects are responsible for most scaling effects, it follows that conventional scale knowledge does not provide the means to comprehensively understand and predict the phenomena at the micro scale. The lack of cavitation knowledge in micro scale has enormous impact on an engineer’s ability to properly design micro power-MEMS devices. As a direct result the Micro Thermal-Fluids Systems Laboratory at Rensselaer Polytechnic Institute has been establishing experimental capabilities to investigate cavitation in micro systems.

This paper seeks to identify differences in cavitation between conventional scale and micro scale devices, and to briefly present major findings from available literature. It also aims to increase awareness and promote future research on cavitation in micro systems. The fluid flow effects and unique devices characteristics which are expected to have profound affects on cavitation in micro scale systems are discussed in section 2. Section 3 presents preliminary results available in the literature. A brief summary is presented in Section 4.

## NOMENCLATURE

| Symbol | Description | Units |
|---|---|---|
| $L$ | characteristic length | m |
| $s$ | Surface tension | N/m |
| $Kn$ | Knudsen number | |
| $P$ | pressure | $N/m^2$ |
| $Re$ | Reynolds number | |
| $We$ | Weber number | |
| $V$ | velocity | m/s |

**Greek**

| | | |
|---|---|---|
| $\lambda$ | mean free patch | m |

$\mu$ viscosity kg/ms
$\rho$ density kg/m$^3$
$\sigma$ cavitation number

**Subscript**
$v$ vapor
$\infty$ free stream

## 2. DIFFERENCES BETWEEN CAVITATION IN MICRO AND CONVENTIONAL SYSTEMS

Various known factors, such as flow dimensionless parameters, component geometries, liquid contaminants (nuclei sources), and surface roughness and chemistry, which affect cavitation in conventional scale systems are altered in micro scale domains. The differences arise from various causes including micro fabrication constraints, typical choice of device material, and the Reynolds number. Low Reynolds number dominated micro flows dictate new optimization envelopes, such as different angles of attack (for pumps), which in turn requires geometrical modification to the components. In an attempt to highlight these differences, this section discusses each factor in detail.

### 2.1 Geometrical effect

Even when ignoring all scaling effects, conventional scale knowledge can not be used to model cavitation in microsystems simply because scaling requires the model and prototype to be geometrically similar. However, microfabricated devices usually possess geometries which are considerably different from their conventional-sized counterparts.

The Deep Reactive Ion Etching (DRIE) [34] technique, first presented in the mid to late nineties, facilitated the fabrication of copious innovative microsystems especially power-MEMS systems. Since most MEMS devices involve some form of lithography-based microfabrication, the use of flat substrates are required. Often, these flat substrates involve the use of DRIE methods and result in structures characterized by extrusion of two-dimensional features into the third dimension as illustrated in Figure 1. Often microfluidic components are restricted in their geometrical appearance due to the fabrication limitations. Therefore, full 3-D shape optimization which is commonly feasible in many large-scale fluidic devices such as pumps hydrofoils, turbine blades and vanes, mixers, etc, is difficult to achieve in MEMS devices.

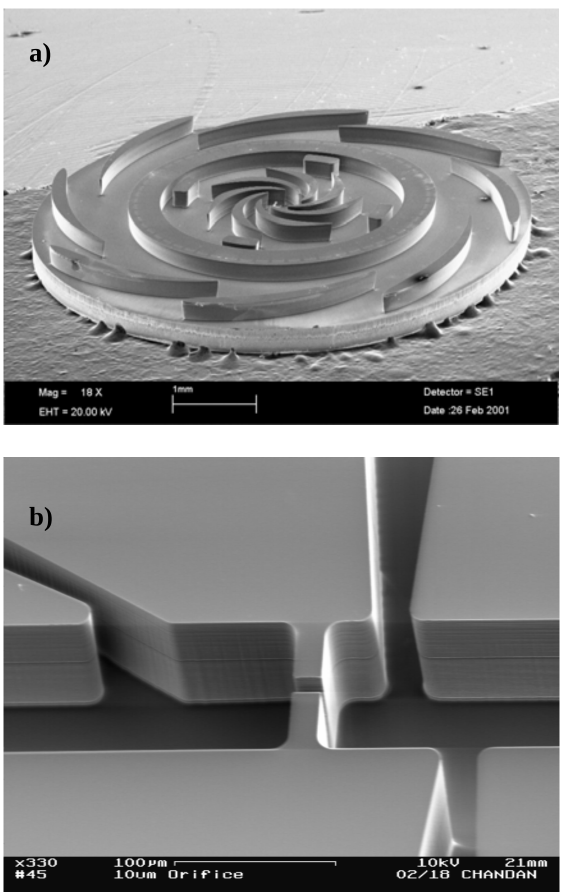


Figure 1. The DRIE methods result in structures characterized by extrusion of two-dimensional features. a) The MIT micro turbo pump rotor [35]), b) Micro scale orifice [36].

### 2.2 Nuclei effect

The term nuclei refers to the impurities that cause weak spots in the liquid and thus prevent the liquid from supporting higher liquid tensions. Generally, nuclei can be categorized into two groups, stream nuclei and surface nuclei. Stream nuclei consist of undissolved gases or uncondensed vapor trapped in solid particles or in microbubbles moving with the flow, while surface nuclei originate in the solid-fluid boundary in the cracks, crevices and other surface imperfections. The importance of nuclei in dictating cavitation events has enticed considerable attention and resulted in various technical investigations. The effects of nuclei on inception, developed cavitation and scaling have been extensively investigated, and methods have been disinterred. Additionally, nuclei concentration detection methodologies have been developed.

In micro systems, the relative size of the stream nuclei and dimension, shape, and chemistry of surface nuclei are altered. Microscale hydraulic devices are fabricated from silicon by various microfabrication etching processes (primarily by DRIE processes), which poses vastly different properties than the material and fabrication methods used in the construction of large-scale hydraulic devices (surface chemistry as well as surface topography). For example, the DRIE process forms

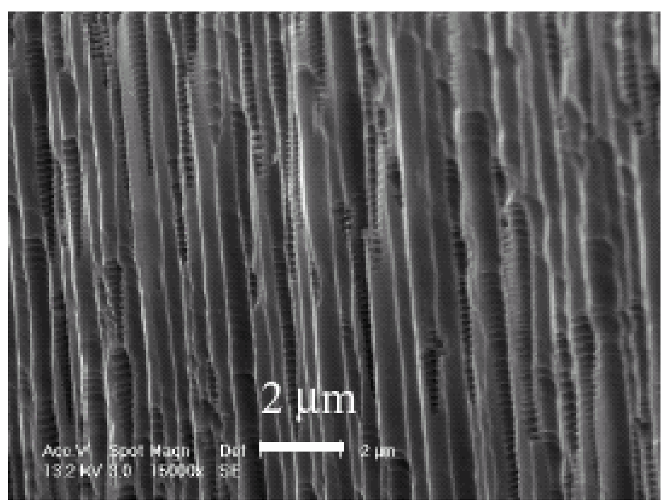


Figure 2. Deep reactive-ion etching results in scalloped sidewalls, with a roughness of ~0.3µm (from Srikar et al.[37])

 

deep trenches on the silicon wafer with a characteristic scalloped sidewall possessing a peak-to-peak roughness of ~0.3μm (Figure 2).

Furthermore, the surface nuclei become increasingly important with respect to the stream nuclei as the length scale diminishes. This can be better understood by considering the time available for the stream nuclei growth. As the system size reduces (for a given velocity value), the dwell-time of a nucleus in the low-pressure region diminishes. Consequently, the nucleus has insufficient time to grow and become active. On the other hand the time available for growth of the surface nuclei is not necessarily hampered as the paragon dimensions drop. The bubble conveniently dwells in the low-pressure region before it is torn from the surface due to the action of drag forces. Based on the Rayleigh-Plesset equation, Mishra and Peles[15] have shown that the time necessary for typical stream nuclei to initiate cavitation in a micro-orifice device is an order of magnitude larger than the resident time spent by the stream nuclei in the low pressure region. The authors concluded that surface nuclei are the dominant species and dictate cavitation events in their microscale device.

It should be noted that most conventional scale investigations have been carried out on tap or natural water, in which the stream nuclei is mainly in the 10-100 μm size range. As stated by the specialist committee on water quality and cavitation [38], a chief criterion for cavitation inception testing is the availability of a sufficient number of micro bubbles in that size range. However, for micro scale devices the applications typically dictate stringent requirements for stream contaminant, which are usually not larger than ~1 μm. Let aside all other differences, it follows that most experimental data on stream nuclei size and distribution are not in the range that is applicable to the working fluid employed in micro scale devices.

### 2.3 Dimensionless flow parameters

Four main dimensionless parameters that govern cavitation in microsystems are the cavitation ($\sigma$), Reynolds (*Re*), Weber (*We*), and Knudsen (*Kn*) numbers defined by the following equations:

$$\sigma = \frac{P_\infty - P_v}{1/2\,\rho V_\infty};\ \mathrm{Re} = \frac{\rho V_\infty L}{\mu};\ We = \frac{\rho V_\infty^2 L}{s};\ Kn = \frac{\lambda}{L}$$

Although early work on cavitation scaling [39] has suggested the *We* number as a possible parameter affecting cavitation, it has been found that nuclei together with viscous effects are responsible for most scaling effects in conventional scale systems, and therefore the primary dimensionless parameters used in large scale systems are the Reynolds and Cavitation numbers (although in some circumstances other dimensionless parameters such as the Froude, Strouhal, Weber, numbers have been employed).

High-velocity microsystems operate at considerably lower Reynolds numbers than their large-scale counterparts. For example, the maximum hydrofoil based Reynolds number of the exceptionally high-speed MIT micro turbopump [35,40], is no more than ~10,000, while at conventional scale typical Reynolds numbers are on the order of ~($10^5$-$10^8$). The vast majority of available data on limited and developed cavitation are for Reynolds number much higher than the range observed/attainable in microsystems. This has important consequences on the extension of conventional data to micro systems because it has long been recognized [41-45] that viscous effects are significant for both inception and developed cavitation. For hydrofoils the problem becomes even more profound since different chord lengths yielded different cavitation inception-Reynolds number curves (e.g. Holl & Wislicenus [39]). This suggests that there is an additional size or speed effect separate from the Reynolds number. Although, Brennen [21] speculated that the ratio of nuclei size to hydrofoil length is the missing parameter, no definite conclusion could be reached in the absence of information on the nuclei.

Although the surface tension force is important in the excitation and initial growth stages of a cavitating bubble, surface forces hardly have any affect on the global flow field once the individual bubble has matured to a substantial macro size. In microsystems, on the other hand, the bubble is unable to grow beyond the micro device domain, and continued to be influenced by surface tension forces since they are dominant at those length scales. It follows that the Weber number (or/and the Capillary number) assumes an increasingly important role as system size diminishes.

The Knudsen number is often used to quantify the deviation of the state of the gas from continuum regime, and to provide guidance for selecting appropriate modeling approaches. The Knudsen number is also used to classify the flow based on its degree of departure from the continuum assumption. A commonly accepted classification is given in Figure 3. When the *Kn* number is smaller than ~$10^{-2}$ the flow is continuous and the Navier-Stokes equation can be used to fully model the flow. For $10^{-2} < Kn < 0.1$ the continuum assumption can still be used provided the no-slip wall boundary condition be replaced by a finite slip velocity. As *Kn* becomes larger the departure from continuum becomes significant, and at *Kn*~0.1 Navier-Stokes equation can no longer be used. For $0.1 < Kn < 10$ a higher order model is commonly used. When *Kn* is larger than ~10 the flow is discrete-particulate and proper modeling requires a molecular dynamic (MD) simulation approach.

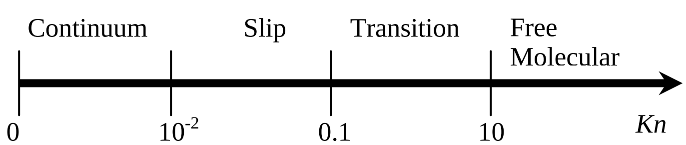


Figure 3. Knudsen number ranges for various flow regimes

Keeping in mind that during cavitation, the prevalent static pressures are significantly lower than atmospheric pressures, it follows that the *Kn* number is always larger than 0.01 for systems with typical length scale less than ~500 μm. Therefore all cavitating vapor flows in micro systems can not be modeled directly by using the continuity assumption without proper modifications.

## 3. PRELIMINARY RESULTS

Copious engineering applications at the micro scale, which require high liquid speeds, have become a reality in the last half decade. It is therefore not surprising that literature concerning cavitation in micro scale devices is not readily available, and to the best of our knowledge less than a handful of studies have been published on this topic [15-19]. Mishra and Peles [15-17] experimentally studied hydrodynamic cavitation in flows through micro-orifices entrenched in microchannels. Their investigations have yielded unexpected results and major deviations from conventional scale behavior. The presence of a strong size scale effect was very notable, and was attributed to the surface tension forces, which are significant at such small scales. Cavitation inception indexes for various orifices and channels sizes obtained from the experiments were much lower than the values obtained from previous studies on larger orifices [46-49]. As shown in Figure 4 a very quick transition from incipient cavitation to choking cavitation (point *B* to *C*) was observed, which is in complete contrast to the trend observed in larger orifices [46-50]. Similar results on micro scale hydrofoil cascades have been observed by Pennathur et al.[18] as shown in Figure 5. This rapid transition from inception to choking cavitation is perhaps an intrinsic characteristic of cavitation in micro-domains, and is

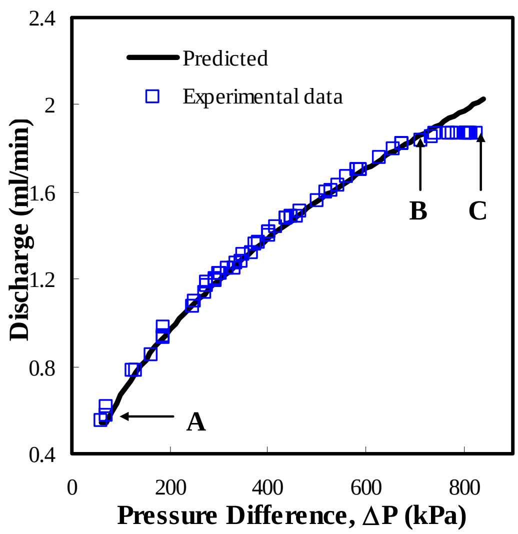


Figure 4. Discharge vs. Pressure drop. Region A-B corresponds to single-phase flow, while region B-C corresponds to cavitating flow [15].

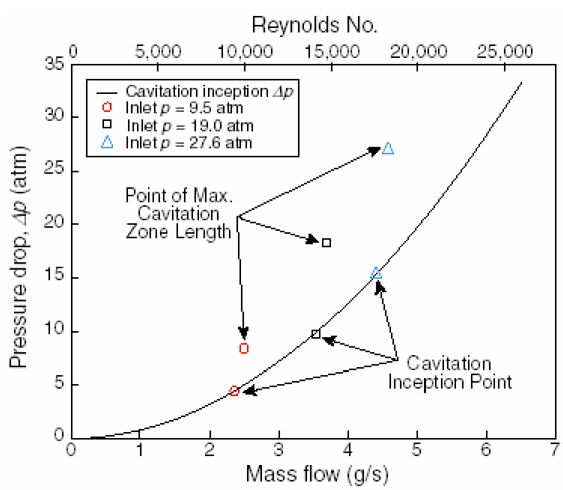


Figure 5. Flow rate vs. pressure drop characteristics of cavitating cascade at fixed inlet pressure [18].

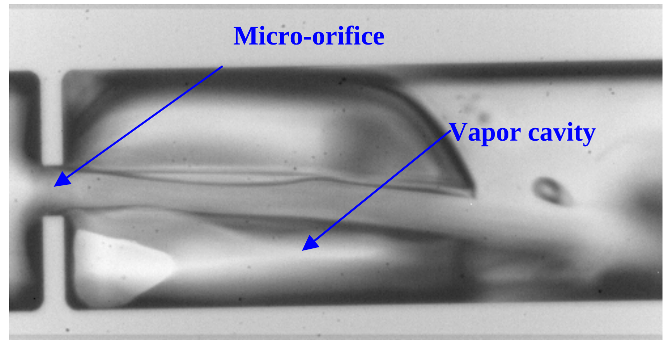


Figure 6. Cavitation through a 40 μm orifice entranced in 200 μm microchannel [17].

probably strongly affected by the increasing surface forces with diminishing length scale. Experimental studies performed with low surface tension fluids (higher Weber numbers) might unveil the role of surface tension forces in control rapid choking.

Depending on the micro-orifice and microchannel sizes, large flow hysteresis was present. It was hypothesized that this flow hysteresis is closely related to the radically different

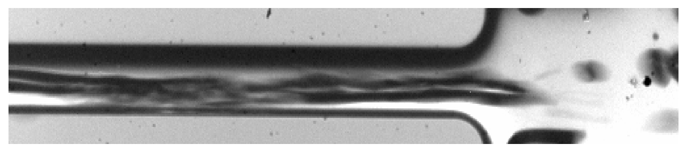

Figure 7. Supercavity extending until the channel exit [17].

cavitation flow patterns exhibited in the smaller devices ($d_h$~10μm and $D_h$~100μm). The larger micro-orifice embedded devices ($d_h$~40μm and $D_h$~200μm) displayed cavitating flow patterns similar to those observed in conventional size orifices (Figure 6). Additionally, different flow patterns were observed during supercavitation, wherein a thick vaporous cavity appeared in the microchannel and was engulfed by the liquid. This supercavity was detected in the center of the microchannel and extended until the channel exit. In larger orifices, twin vapor cavities were observed encompassing a thick liquid jet (Figure 7), which breaks up after hitting the walls of the pipe downstream of the orifice. Upon reducing the cavitation number, the twin cavities merge further downstream forming a supercavity. It is apparent that flow pattern differences in micro and macro scale orifices and channels are present. However, currently no criterion exists that can describe/ quantify this condition leading to the flow regime transition.

Hydrodynamic cavitation, in the context of a high speed (750,000-1,200,000 rpm) MEMS turbopumps being developed for millimeter-scale, liquid bipropellant, high-pressure rocket engines [1,35,40] has been experimentally investigated for working fluids like water and ethanol by Pennathur et al.[18] and Pennathur [19] with 900 micron hydrofoil cascades, which are characteristic of the centrifugal micro-pump used in the MIT micro turbo-pump. It was found that cavitation would seriously affect the efficiency and performance of the pump. The above investigation instigated two cardinal design changes wherein the pump inlet pressure was raised, and a secondary boost pump was added in series with the main pump to produce

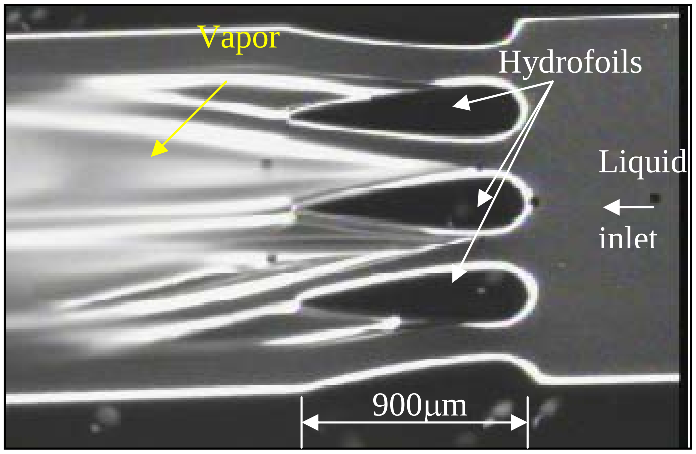

Figure 8. Cavitation in micro hydrofoils [18].

the required pumping power. The experimental part of this research demonstrated that cavitation is clearly part of the engineering environment of MEMS hydraulic devices as exemplified by Figure 8, and cavitation concerns are as important as they are in large-scale fluid devices (and perhaps even more so due to the quick transition from inception to choking). One very interesting finding was the significant suppression of cavitation upon the removal of 20 μm ports, designed to measure pressure in the vicinity of the hydrofoil. This evidence that clearly demonstrate the importance of surface nuclei in micro scale cavitation, and further justify the call for conducting comprehensive investigations on cavitation occurring in microfluidic systems.

## 4. SUMMARY

Based on the discussion presented above, current cavitation knowledge on micro scale devices can be summarized as follows: a) it is a fundamental problem which is very poorly understood, b) The lack of understanding of cavitation pertinent to microscale systems is seriously affecting the practical realization of multifarious neoteric high-velocity micro scale fluid machines. Additional conclusions can also be drawn by conducting a literature review on cavitating flows in microsystems and conventionally sized systems:

- Scaling effects of cavitation have been extensively investigated at the conventional scale, however, they are at best applicable for scaling between prototypes and real-world paragons at the macro-scale. Conventional scale knowledge has shown that the scaling effects associated with assorted nuclei, influence cavitation significantly.
- Archival research literature concerning cavitation in micro scale systems is exceedingly limited. An investigation of cavitation in microfluidic devices is exigent and imperative for the successful realization of numerous novel micro machines.
- From the limited studies that have been conducted many anomalies have been found between cavitation in microsystems and cavitation in their conventional scale counterparts. Unique flow patterns, very low cavitation inception indexes, excessive hysteresis under some conditions, and very quick transition from inception to choking cavitation, are all distinctive characteristics of cavitating flows in micro scale components.
- The strong scale effect observed for cavitation in micro systems is likely to be influenced by surface tension forces, which are significant at such small scales.
- Surface nuclei are expected to become increasingly more important than stream nuclei at the micro scale.

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**REFERENCES**

[1]A.P. London, A.A. Ayon, A.H. Epstein, S.M. Spearing, T. Harrison, Y. Peles, J.L. Kerrebrock, "Microfabrication of a high pressure bipropellant rocket engine," Sens. and Actuators A92, 351 (2001).
[2]A.A. Alexeenko, S.F. Gimelshein, D.A. Levin, A.D. Ketsdever, M.S. Ivanov, "Measurements and simulation of orifice flow for micropropulsion testing," J. Prop. Power 19, 588 (2003).
[3]J. Mueller, I. Chakraborty, S. Vargo, C. Marrese, V. White, D. Bame, R. Reinicke, J. Holzinger, "Towards micropropulsion systems on-a-chip: initial results of component feasibility studies," IEEE Aero. Conf. Proc., Piscataway, USA (2000), p. 149.
[4]J. Mueller, E.-H. Yang, A.A. Green, V. White, I. Chakraborty, R. Reinicke, "Design and fabrication of MEMS-based micropropulsion devices at JPL," SPIE 4558, 57 (2001).
[5]J. Burger, H. Holland, E. Berenschot, J.-H. Seppenwodde, M. TerBrake, H. Gardeniers, M. Elwenspoek, "169 kelvin cryogenic microcooler employing a condenser, evaporator, flow restriction and counterflow heat exchanger," 14th IEEE Conf. on MEMS, Piscataway, USA (2001), p. 418.
[6]M.V. Zagarola, J.J. Breedlove, J.A. McCormick, W.L. Swift, "Turbo-Brayton cryocooler technology for low-temperature space applications," SPIE, 4850, 1029 (2003).
[7]R. Leoni, "On-chip micro-refrigerators for sub-Kelvin cooling," New Astro. Rev. 43, 317 (1999).
[8]H. Helvajian, P.D. Fuqua, W.W. Hansen, S. Janson, "Laser microprocessing for nanosatellite microthruster applications," HRIKEN Rev. 32, 57 (2001).
[9]A.A. Ayon, R.L. Bayt, K.S. Breuer, "Deep reactive ion etching: a promising technology for micro and nanosatellites," Smart Materials and Struct. 10, 1135 (2001).
[10]S.W. Janson, "Micro/ nanotechnology for the satellite world," SPIE 4981, 95 (2003).
[11]L.R. Arana, S.B. Schaevitz, A.J. Franz, K.F. Jensen, M.A. Schmidt, "A microfabricated suspended-tube chemical reactor for thermally efficient fuel processing," J. Microelectromech. Sys. 12, 600 (2003).
[12]M.W. Losey, R.J. Jackman, S.L. Firebaugh, M.A. Schmidt, K.F. Jensen, "Design and fabrication of microfluidic devices for multiphase mixing and reaction," J. Microelectromech. Sys. 11, 709 (2002).
[13]A. Marshall, J. Hodgson, "DNA chips: An array of possibilities," Nature Biotech. 16, 27 (1998).
[14]R.C. Anderson, G.J. Bogdan, Z. Bamiv, T.D. Dawes, J.

 

Winkler, K. Roy, “Microfluidic biochemical analysis system,” Proc. Int. Conf. on Solid-State Sens. and Actuators, Chicago, USA (1997), p. 477.
[15]C., Mishra and Y., Peles, “Cavitation in Flow Through a Micro-Orifice Inside a Silicon Microchannel,” *Physics of Fluids*, 17(1), 2005.
[16]C., Mishra and Y., Peles, “Size Scale Effects on Cavitating Flows Through Micro-Orifices Entrenched in Rectangular Microchannels,” *Journal of Microelectromechanical Systems*, 2005 (accepted).
[17]C., Mishra and Y., Peles, “Flow Visualization of Cavitating Flows Through a Rectangular Slot Micro-Orifice Ingrained in a Microchannel” submitted to *Physics of Fluids*, 2005.
[18]S., Pennathur, Y., Peles, and A.H., Epstein, “Cavitation at Micro-Scale in MEMS Fluid Machinery,” Proceeding of IMECE’02, *ASME International Mechanical Engineering Congress & Exposition*, New Orleans, Louisiana, November 17-22, 2002.
[19]S. Pennathur, “Micro-scale turbopump blade cavitation,” M.S. Thesis, Massachusetts Institute of Technology, Cambridge, MA (2001).
[20] R.E.A. Arndt, “Cavitation in fluid machinery and hydraulic structures,” Ann. Rev. Fluid Mech. 13, 273(1981).
[21]C.E. Brennen, *Cavitation and Bubble Dynamics* (Oxford University Press, Oxford, UK, 1995).
[22]R.T. Knapp, J.W. Daily, F.G. Hammit, *Cavitation* (McGraw-Hill, New York1970).
[23]M.S. Plesset, “The dynamics of cavitation bubbles,” J. Appl. Mech. 16, 277 (1949).
[24]L. Rayleigh, “On the pressure developed in liquid during the collapse of spherical cavity,” Phil. Mag. 34, 94 (1917).
[25]F.R. Young, *Cavitation*, (McGraw-Hill, New York, 1989).
[26]E.N. Harvey, W.D. McElory, “On the cavity formation in water,” J.Appl. Phys. 18, 162 (1947).
[27]D.D. Joseph, A. Prosperetti, “Cavitation and the state of stress in a flowing liquid,” J. Fluid Mech. 366, 367 (1998).
[28]B. Ran, J. Katz, “The response of microscopic bubbles to sudden changes in the ambient pressure,” J. Fluid Mech. 224, 91 (1991).
[29]Y. Tomita, A. Shima, “Mechanisms of impulsive pressure generation and damage pit formation by bubble collapse,” J. Fluid Mech. 169, 535 (1986).
[30]J.R. Blake, D.C. Gibson, “Cavitation bubbles near boundaries,” Ann. Rev. Fluid Mech. 19, 99 (1986).
[31]A. Karimi, F. Avellan, “Comparison of erosion mechanisms in different types of cavitation,” Wear 113, 305 (1986).
[32]R. Young, “Cavitation in pumps, pipes and valves,” Process Engg. 71, 47 (1990).
[33]D.R. Stinebring, “Analysis of cavitation damage on the space shuttle main engine high pressure oxidizer turbopump,” ASME Fluids Engg. Div. 25, 71 (1985).
[34]F. Lärmer and P. Schilp, “Method of anisotropically etching silicon,” German Patent DE 4241045, 1994.
[35] A. Deux, M.S. Thesis, Design of a silicon microfabricated rocket engine turbopump, Massachusetts Institute of technology, Cambridge, MA, USA, (2001).
[36]C., Mishra and Y., Peles, “Incompressible and Compressible Flows Through Rectangular Micro-Orifices Entrenched in Silicon Microchannels,” submitted to *Journal of Microelectromechanical Systems*.
[37] V. T., Srikar, Y. Peles, L.R. Arana, and S.M. Spearing, “Self-Assembly of Micro- and Nanoparticles on Internal Micromachined Silicon Surfaces,” Sensors and Actuators A 113, 124 (2004).
[38] The specialist committee on water quality and cavitation, Final report and recommendations to the 23rd ITTC, Proceeding of the 23rd ITTC, Vol. 2, pp. 451-483, Venice, Italy, September 8-14, 2002.
[39] J.W Holl and G.F. Wislicenus, “Scale effect on cavitation,” Journal of basic engineering 83, 385 (1961).
[40] L. Jamonet, M.S. Thesis, Massachusetts Institute of technology, Cambridge, MA, USA, 2002.
[41]V.H. Arakeri & A.J. Acosta, Viscous effects in the inception of cavitation on axisymmetric bodies, Journal Fluids Engineering 95, 519 (1973).
[42]V.H. Arakeri, “Viscous effects on the position of cavitation separation from smooth bodies,” Journal of Fluid Mechanics 68, 779 (1975).
[43]J.H.J. Van Der Meulen, “A holographic study of the influence of boundary layer and surface characteristics on incipient and developed cavitation on axisymmetric bodies,” In proc. Of the 12th symp. On naval hydrodynamic, Washington, USA, (1978) p.433-451.
[44]J.H.J. Van Der Meulen, “Boundary layer and cavitation studies of Naca 16 012 and Naca 4412 hydrofoils,” In proc. Of the 13th symp. On naval hydrodynamic, Tokyo, Japan, (1980), p.195.
[45]M.L. Billet and J.W. Holl, “Scale effect on various types of limited cavitation,” Journal of fluids engineering 103, 405 (1981).
[46] Y. Yan, R.B. Thorpe, “Flow regime transitions due to cavitation in the flow through an orifice,” Int. J. Multiphase Flow 16, 1023 (1990).
[47] J.P. Tullis, “Choking and supercavitating valves,” *J. Hydr. Div.*, HY12, pp. 1931-1945, 1971.
[48]J.P. Tullis, R. Govindarajan, “Cavitation and size Scale effect for orifices,” *J. Hydr. Div.*, vol. 99, pp. 417-430, 1973.
[49] K. Ramamurthi, K. Nandakumar, “Characteristics of flow through small sharp-edged cylindrical orifices,” *Flow Measurement. and Instr.*, vol. 10, pp. 133-143, 1999.
[50]J.P. Tullis, *Hydraulics of Pipelines*, (John Wiley & Sons Inc., New York, USA, 1989).

 